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Assessing land use and flood management impacts on ecosystem services in a river landscape (Upper Danube, Germany)

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Abstract

Rivers and floodplains provide many regulating, provisioning and cultural ecosystem services (ES) such as flood risk regulation, crop production or recreation. Intensive use of resources such as hydropower production, construction of detention basins and intensive agriculture substantially change ecosystems and may affect their capacity to provide ES. Legal frameworks such as the European Water Framework Directive, Bird and Habitats Directive and Floods Directive already address various uses and interests. However, management is still sectoral and often potential synergies or trade-offs between sectors are not considered. The ES concept could support a joint and holistic evaluation of impacts and proactively suggest advantageous options. The river ecosystem service index (RESI) method evaluates the capacity of floodplains to provide ES by using a standardized five-point scale for 1 km-floodplain segments based on available spatial data. This scaling allows consistent scoring of all ES and their integration into a single index. The aim of this article is to assess ES impacts of different flood prevention scenarios on a 75 km section of the Danube river corridor in Germany. The RESI method was applied to evaluate scenario effects on 13 ES with the standardized five-point scale. Synergies and trade-offs were identified as well as ES bundles and dependencies on land use and connectivity. The ratio of actual and former floodplain has the strongest influence on the total ES provision: the higher the percentage and area of an active floodplain, the higher the sum of ES. The RESI method proved useful to support decision-making in regional planning.

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1 | INTRODUCTION

Rivers and floodplains provide many benefits to humans (Schindler et al., 2014). From an ecological perspective, rivers and floodplains are hotspots of biodiversity as they host diverse abiotic conditions and are subject to dynamic disturbances leading to a mosaic of many specific habitats and species (Robinson, Tockner, & Ward, 2002; Ward, Tockner, & Schiemer, 1999). River landscapes also provide water resources, fertile soils for plant production and aquatic resources such as fish. They help to regulate nutrient cycle, local climate as well as water and air quality. In addition, rivers and their surrounding landscapes offer diverse opportunities for recreation (e.g., swimming, fishing, boating). The diverse landscape of river courses and active floodplains are considered highly valuable regarding landscape aesthetic quality (Thiele, von Haaren, & Albert, 2019). However, extraordinary high floods may bring risks to settlements, infrastructure, and other land use types in floodplains. To cope with these risks, rivers and floodplains have been modified for more than 150 years leading to strongly altered hydromorphological conditions and a separation of rivers from their adjacent floodplains mainly through dams and embankments (Diaz-Redondo, Egger, Marchamalo, Hohensinner, & Dister, 2017; Hohensinner, Jungwirth, Muhar, & Schmutz, 2014). Especially in Europe and North America, more than 80% of all rivers have been affected by impoundments (Nilsson, Reidy, Dynesius, & Revenga, 2005). For instance, the Danube River in Europe has 83 barriers along its entire length, the majority of them being located in the upper part of the river and used for hydropower production; only a third of them are passable for fish heading upstream. Its floodplains have been reduced by 68% of their former extension (Hein et al., 2016). In the German part, up to 90% of the Danube floodplains have been disconnected from the river by dikes (Brunotte, Dister, Günther-Diringer, Koenzen, & Mehl, 2009). This intensive human impact threatens the unique multi-functionality and processes of riverine ecosystems. Hence, several sectors like water quality management, nature conservation or flood defence reacted to these threats by creating new legislation and plans, for instance the EU Water Framework Directive, the EU Bird and Habitats Directives or the EU Floods Directive. Such approaches, however, have failed to integrate all sectoral interests or to consider potential synergies and trade-offs. Therefore, the need for an integrative multi-functional management of rivers and floodplains has been widely recognized, while practical approaches for this are still missing (Dufour & Piégay, 2009; Hein et al., 2019).

The concept of ecosystem services (ES) highlights the importance of ecosystems for human well-being and may contribute to taking better account for biodiversity in planning and decision-making. ES can be categorized into provisioning, regulating and cultural ES (Millennium Ecosystem Assessment, 2005; Haines-Young & Potschin, 2013). The ES concept enables to evaluate management options holistically and to identify best solutions (De Groot, Alkemade, Braat, Hein, & Willemen, 2010; Turner et al., 2016). Such evaluation is particularly relevant for multi-functional floodplains where ES trade-offs and synergies frequently occur (Hanna, Tomscha, Ouellet Dallaire, & Bennett, 2018; Rouquette et al., 2011; Schindler et al., 2014). By evaluating all relevant ES, a cross-sectoral assessment of river and floodplain management options in general is possible (Hornung, Podschun, & Pusch, 2019). A variety of methods and tools may be used to assess and map ES and support decision-making (Bagstad, Semmens, Waage, & Winthrop, 2013; Maes et al., 2012; Turner et al., 2016). ES mapping can reveal diverging use and interests, for example, between agriculture, flood defence, nature conservation, and can support deriving solutions to mitigate these conflicts and to harness synergies (Harrison et al., 2018; Tomscha, Gergel, & Tomlinson, 2017). Proxy-based methods (e.g., based on land cover or land use) have already been widely used to estimate large-scale patterns of ES in floodplains (Clerici, Paracchini, & Maes, 2014; Large & Gilvear, 2015; Stürck, Poortinga, & Verburg, 2014). In addition, data derived from biological monitoring, yield statistics, hydrological modelling or interviews on recreation can enhance the level of detail (Burkhard, Kroll, Nedkov, & Müller, 2012; Fischer et al., 2019; Tomscha et al., 2017). Yet a spatially explicit quantifying assessment of all ES in floodplains represents a persistent challenge (Hanna et al., 2018; Keele, Gilvear, Large, Tree, & Boon, 2019), often mainly limited by the lack of suitable data. To address this knowledge gap, Podschun et al. (2018) developed the RESI (river ecosystem service index) as an evaluation tool for 16 ES relevant for rivers and floodplains relying on available spatial data.

An important knowledge gap currently exists regarding how different ES relate to spatial parameters and changes over time. Such information could provide useful information to support policy and management of rivers and floodplains regarding where and when interventions should be targeted. For assessing such relationships, recent research has begun to assess interdependencies between different ES (Keele et al., 2019; Large & Gilvear, 2015), between ES and spatial parameters, and to identify bundles of ES depending on similar conditions (Raudsepp-Hearne, Peterson, & Bennett, 2010; van der

Biest et al., 2014; Van Looy, Tormos, Souchon, & Gilvear, 2017). The effect of temporal parameters like natural periodical fluctuations or management aspects on ES in river landscapes and the challenge of integrating them into landscape planning was demonstrated by Bastian, Grunewald, and Syrbe (2012). Such information on relationships between ES and spatial parameters and for different scenarios could be particularly useful in case of the Danube River in Germany as the Danube is subject to several sectoral development plans. This offers the opportunity of a comprehensive analysis by mapping multiple ES to derive an integrative management.

The aim of this article is to explore ES impacts of different flood prevention scenarios on a 75 km section of the Danube river corridor. We used the RESI method (Podschun et al., 2018) to evaluate the capacity of river and floodplain to provide all regional relevant ES with a standardized five-point scale. The 1 km-floodplain segments, widely established in Germany (Brunotte et al., 2009), were used as unit for the evaluation based on spatial data. Our research objectives are threefold:

1. To explore the current (status quo) provision of ES in relation to land use, reduction of active floodplain area and floodplain width in this heavily affected floodplain;
2. to identify synergies and trade-offs between individual ES and ES bundles;
3. to demonstrate the power of the RESI method by evaluating the effect of different flood risk scenarios on the total set of ES.

2 | STUDY AREA

We studied a floodplain corridor along the Danube River in Bavaria, Germany, between the two tributaries Iller and Lech (Figure 1a). Annual mean discharge of this Danube section (gauge Dillingen/Donau) is 162 m^3 s^{-1} and mean high discharge is 700 m^3 s^{-1} (Landesamt für Umwelt [LfU], 2019). Within this 75 km stretch, representative for the very upper part of the river where navigation is not possible (ca. 400 km), there are nine dams used for hydropower generation, each associated with dikes of 2.5–5 km separating the river from the floodplain. This has reduced the available flood retention area in the originally up to 10 km wide floodplain (active floodplain) by 62% (Figure 1b). Land use (GeoBasis-DE/BKG, 2016, see Appendix S1) in the studied river corridor consists mainly of agricultural land (42.5%), grassland (22.0%), forest (18.7%) and settlements (10.2%) (Figure 1c). Woodlands dominate the smaller upstream sections, whereas arable land with partly larger shares of grassland dominate the wider downstream sections.

3 | METHODS

ES provision was assessed according to the RESI approach (Podschun et al., 2018, www.resi-project.info) by proxy-based algorithms. The exact methods and the used data were published in Fischer et al. (2020), its subchapters as well as additional literature are summarized in Table 1 for the individual ES. The RESI approach uses data sources those are available including public data as well as administrative data (available upon request).The data types include Germany wide data (e.g., land cover model, digital terrain model, weather data, soil map, cultural heritage data), data related to the monitoring of the Water Framework Directive (e.g., river quality mapping, water quality data) as well as more regional data such as agricultural soil values, nature conservation sites and habitat mapping (see Table 1, Appendix S1). According to the available data in this river section, 13 ES were assessed representing the three ES classes provisioning (crops), regulating (nitrogen retention, phosphorous retention, flood risk regulation, drought risk regulation, mass flow/sediment regulation, soil formation, local climate regulation/cooling effects, habitat provision) and cultural ES (landscape aesthetic quality, heritage, opportunities for water-related and non-water-related activities). All ES were evaluated for 1 km-floodplain segments (according to the national setting for floodplains [Brunotte et al., 2009]) in an ordinal scale of five classes, where one means no or a very low and five means a very high value for ES provision. ES were calculated with GIS ArcMap 10.x. Each individual ES can be mapped, which is shown here exemplarily for the detention basin Leipheim to illustrate substantial scenario impacts. Additionally, all ES values were summed up to one index (RESI).

3.1 | Scenarios

For nine ES the values were also calculated for flood risk prevention scenarios by adjusting the proxies (e.g., land use, flooding regime) to the assumed situation. For cultural ES the assessment was based on so many parameters that a simple adjustment was not feasible. Two different scenarios were considered, both of which aim to improve flood protection for settlements in this river stretch. The Bavarian state government identified three potential locations for detention basins (polders) and six uncontrolled flood retention areas (Figure 1b, c). Two different management options for these areas were elaborated: The smaller Scenario 1 only includes existing woodlands and water bodies to be regularly flooded for ecological purposes (up to three times a year), whereas the larger Scenario 2 also includes agricultural land and will only be flooded during extreme floods (HQ_{50} and higher) in order to reduce peak discharges in downstream sections. The exemplarily presented polder Leipheim covers 506 ha in Scenario 1 and 621 ha in Scenario 2.

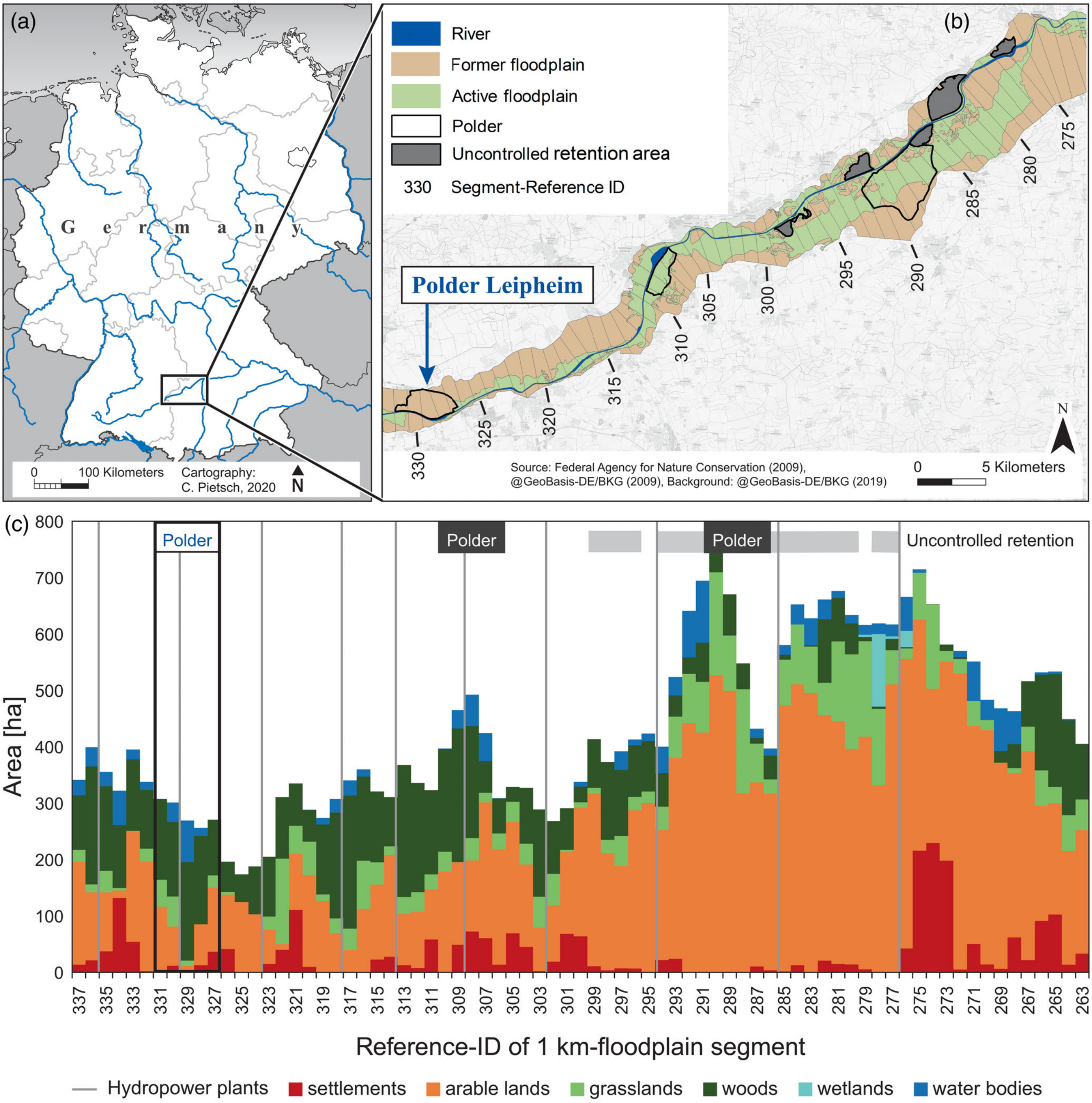
3.2 | Statistical analysis

Relationships between the assessment indices were analysed using the non-parametric Spearman's rank correlations for all calculated ES per segment with each other, with land use data from the digital land use model (LBM; Landbedeckungsmodell; GeoBasis-DE/BKG, 2016, see Appendix S1) using Corine land cover classes, and with floodplain characteristics (area and percentage of active and former floodplain; floodplain data Federal Agency of Nature Conservation [2009]) using the IBM SPSS Statistics 24 software. A principal component analysis (PCA) on the ES assessments in single floodplain segments was carried out with the programme PC-ORD 6.08. To indicate the spatial overlap of ES and the land use and floodplain parameters for each segment, these parameters were fitted on the PCA ordination plot.

4 | RESULTS

4.1 | Status quo

The provision of several ES varies strongly along the 75 km stretch (Figure 2): Seven ES (all four cultural ES, P retention, drought risk regulation, soil formation) cover the whole range of values from



Source: Federal Agency for Nature Conservation (2009), @GeoBasis-DE/BKG (2009), Background: @GeoBasis-DE/BKG (2019)

FIGURE 1 (a) Location of the study area in Germany; (b) active and former (protected by dikes) floodplains divided in 1 km-segments. Location of the polder Leipheim at which the different scenarios were compared to the status quo; (c) actual land use types within the studied 75 km-floodplain section along the Danube following the direction of flow, Source: Corine Land Cover Data 2012. Grey vertical lines indicate the position of the hydropower barrages. In the upper part, the planned locations of the retention areas are plotted for the uncontrolled area (light grey horizontal bars) and for the polders (dark grey horizontal bars). The polder Leipheim is indicated by the black box

TABLE 1 ES of relevance in the study area, selected from all ES in Podschun et al. (2018) where a general overview of all methods and needed data is given with references to their methodology, data source, necessary indicators/proxies, the unit of measure and the range prior to transformation

Ecosystem Services (ES)	Method description, data source	Indicators/proxies	Unit/scale and range
Provisioning ES			
Crop production	Dehnhardt, Rayanov, Hartje, Sander, and Benner (2020)	1. Potential for agricultural yield (based on soil quality). 2. Risk of flooding	0–50 dt ha^{-1}
Regulating ES			
Nitrogen retention (N ret)	Ritz et al. (2020); Kirchesch, Bergfeld-Wiedemann, and Fischer (2016); Schulz-Zunkel et al. (2012); Natho, Venohr, Henle, and Schulz-Zunkel (2013)	The indicator is calculated by combining the following three separate indicators (italicized): *Annual retention rate per river-km* calculated by the model QSim based on 1. Biological parameter 2. Physicochemical parameter 3. Hydrology 4. River morphology 5. Meteorology *Annual N retention rate per floodplain-km*, proxy-based: 1. Delineation of the active floodplain area 2. Soil type 3. Land use 4. Ecological floodplain status	t a^{-1} per 1 km segment transformed to ‰ and transformed according to river size range 0–0.5
Phosphorus retention (P ret)	Ritz et al. (2020); Kirchescher, Bergfeld-Wiedemann, and Fischer (2016); Schulz-Zunkel et al. (2012)	The indicator is calculated by combining the following two separate indicators (italicized): *Annual P retention rate per river km and phosphorous load*, calculated similar to N retention by QSim *Annual P retention rate per floodplain-km*, proxy-based: 1. Delineation of the active floodplain area 2. Land use 3. Hydraulic roughness	t a^{-1} per 1 km segment transformed to ‰ and transformed according to river size range 0–0.5
Flood risk regulation (flood)	Mehl, Hoffmann, and Iwanowski (2020)	1. Proportion of active flood retention area to potential flood retention area 2. Hydraulic roughness	Continuous data (% area) and ordinal scale WFD (7: Bad–1: Good) combined to finale range 1–5
Drought risk regulation (drought)	Mehl et al. (2020)	1. Morphology of the water bank and river bed (cross-sectional shape, hydraulic roughness, run length, river bend morphology) 2. Backwater (natural, anthropogenic)	Several data sets of ordinal scale WFD (7: Bad–1: Good) combined to finale range 1–5
Mass flow/sediment regulation (sediment)	Mehl et al. (2020)	1. Natural morphological balance of the river bed regarding to the sediment budget	Several data sets of ordinal scale WFD (7: Bad–1: Good) combined to finale range 1–5
Soil formation in floodplains (soil)	Mehl et al. (2020)	1. Distance to groundwater table 2. Potential of formation of alluvial soils	Several data sets of ordinal scale WFD (7: Bad–1: Good) combined to finale range 1–5
Local temperature regulation/ cooling (cooling)	Mehl et al. (2020)	Proportion of real evapotranspiration (ETR) to potential evapotranspiration (ETP) from April–September based on 1. Hydro-meteorological values 2. Soil 3. Land cover 4. Distance to groundwater table	Length as well as area and distance measures combined to 0–100%

(Continues)

TABLE 1 (Continued)

Ecosystem Services (ES)	Method description, data source	Indicators/proxies	Unit/scale and range
Habitat provision (habitat)	Fischer et al. (2019)	1. Habitat types 2. Altered flooding regime 3. Back water influence 4. Conservation status of habitat types 5. Characteristic species	Combination of factors and look-up tables to the ordinal scale 1–5
Cultural ES			
Landscape aesthetic quality (LAQ)	Hermes, Albert, and von Haaren (2018); Thiele et al. (2019)	1. Landscape diversity 2. Landscape naturalness 3. Landscape uniqueness	Quantity and area calculation summarized on a 0–100 scale
Heritage (H)	Thiele, Albert, Hermes, and von Haaren (2020)	1. Density of monuments and cultural-historical facilities 2. Density of archaeological monuments 3. Density of natural monuments	Quantity and area calculation summarized on a 0–100 scale
Opportunities for non-water-related activities (nWA)	Thiele et al. (2020)	1. Presence of banks 2. Possibility to experience the terrain 3. Presence of protected areas	Quantity and area calculation summarized on a 0–100 scale
Opportunities for water-related activities (WA)	Thiele et al. (2020)	1. Water surface area 2. Sand and sandbanks 3. Riparian vegetation 4. Visibility depth 5. Minimum width for non-motorized boating 6. Minimum width for motorized boating 7. Presence of meander 8. Structural quality	Quantity and area calculation summarized on a 0–100 scale

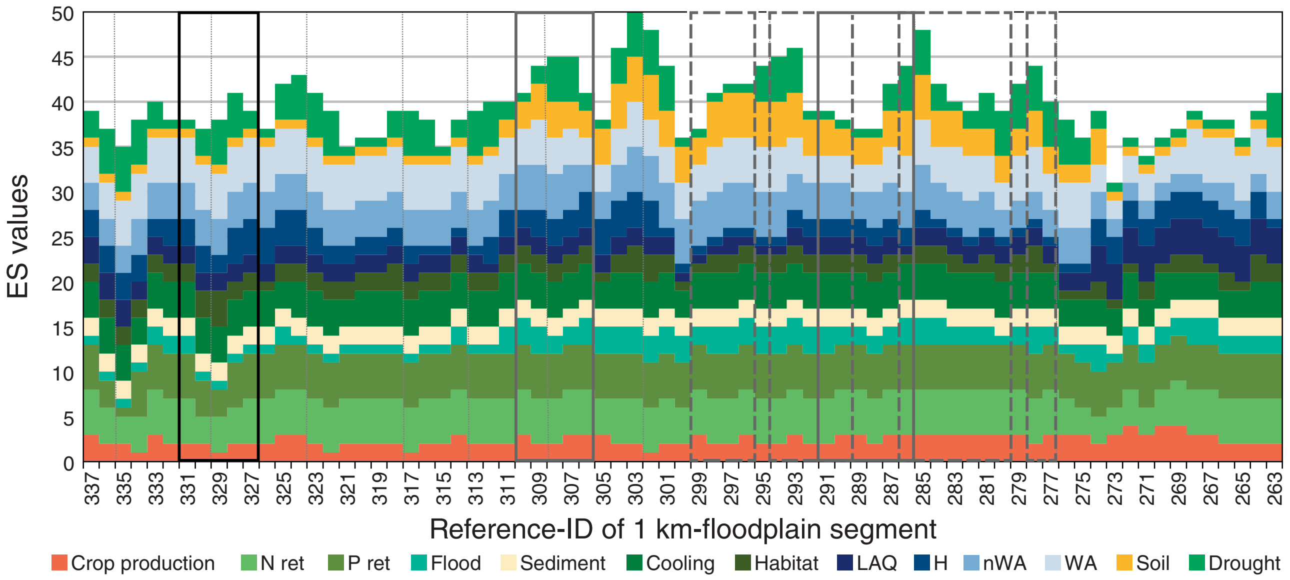


FIGURE 2 Spatial distribution of the provided ES value scores (from 1 to 5 per ES) along the 75 km stretch of the Danube from the west to the east (in flow direction) for the status quo. Abbreviation of ES according to Table 1 (N: nitrogen, ret: retention, P: phosphorous, LAQ: landscape aesthetic quality, H: heritage, (n)WA: (non-)water-related activity). Grey vertical lines indicate the position of the hydropower barrages. The black box indicates the polder Leipheim analysed in Figure 4, grey boxes indicate further polders, dashed grey boxes show the location of the uncontrolled retention areas

1 (very low) to 5 (very high), two ES reach values from 1 to 4 (crops, habitat provision). In contrast, sediment regulation is equally rated low (2) along the whole stretch, cooling varies only from 3 to 4, N retention from 3 to 5, flood risk regulation from 1 to 3. Especially crops, the cultural ES and the regulating ES habitat provision, soil formation and drought risk regulation show heterogeneous evaluations along the 75 km stretch. The sum of all ES values varies clearly between the segments (Figure 2). The maximum RESI of 50 (equalling a mean of

3.8 per ES with values for single ES ranging from 1 to 5) is opposed to the minimum of 31 (equalling a mean of 2.4 per ES with again values for single ES ranging from 1 to 5). Areas with a high RESI are found in the middle of the 75 km river stretch, whereas the lowest amounts lie at the downstream parts.

The PCA ordination (Figure 3) clearly separates the three ES categories (provisioning, regulation and cultural) from each other. Principal component 1 corresponds to a land use gradient from woodland to arable land and explains 27.8% of the total variance of the ES scores. Principal component 2 explains 20.2% of the ES variance and corresponds to a gradient from former to active floodplain area. The ES heritage and landscape aesthetic quality are clearly separated from the other ES, showing a positive correlation with the percentage of former (diked) floodplain. The cultural ES water-related activities, the regulating ES habitat provision and drought risk regulation are positively correlated to woodland. Another bundle consisting of the ES N and P retention, soil formation and flood risk regulation is correlated with the area and percentage of active floodplain. In the PCA, crops, distinctly separated from other ES, are—as expected—strongly correlated with the area of arable land. Synergies and trade-offs between the ES were explored by correlations which support the results of the PCA (Table 2, lower part). Landscape aesthetic quality correlates negatively with soil formation, cooling effects and non-water-related activities, and positively with heritage, whereas the regulating ES show only positive dependencies with each other. Crops show negative correlation with habitat provision and water-related activities. In contrast, non-water-related activities show a positive correlation with cooling.

The individual ES show many strong positive and negative correlations with spatial land use/floodplain characteristics (Table 2, upper part). The area of the 1 km-segments (basically representing the floodplain width), area as well as percentage of the river, active and former floodplain all correlate with 4–6 ES. The land use types with the most positive and negative correlations are arable land (n = 6) and woodlands (n = 3), whereas grassland, wetlands and lakes with only small areas hardly correlate with any ES. Most ES correlate with four or up to seven spatial characteristics. Landscape aesthetic quality correlates only with three spatial characteristics, for sediment regulation no calculation was conducted as its index value always remains the same. The RESI (total sum of ES scores) shows negative correlations with the former (diked) floodplain (area: r = –.60, p < .001, percentage: r = –.71, r < .001) and positive ones with the active floodplain (area: r = .55, p < .001; percentage: r = .68, p < .001), but none with land use types.

4.2 | Scenarios

The two scenarios illustrate different effects of the two types of measures (uncontrolled flooding areas versus polders) on ES. The uncontrolled flooding areas show less response in their provision of ES. In Scenario 1, only one segment shows an increase originating from a higher habitat provision, whereas in Scenario 2, five segments change their value: four segments decrease, one increases. For the polder areas, stronger effects are observed. In Scenario 1, five segments increase their total ES sum, with a maximum increase of 9 (evolving from higher values for the ES N and P retention, flood risk regulation, soil formation and habitat provision). Six segments decrease their value by −1 or −2 (due to decrease in crop production, soil formation and habitat provision), three increase it by 1 due to the increase in flood risk regulation.

Focusing on the segments of polder Leipheim, differences in ES provision can be shown with a focus on the three most affected ES (agricultural crops, flood risk regulation and habitat provision; see Figure 4). Agricultural crops are rated as very low in the status quo. They will not be affected by Scenario 1 but by Scenario 2 as arable fields will be flooded in case of extreme events. Flood risk regulation exhibits a very low value (1) in the status quo and would increase in both scenarios by two classes to a medium provision (3). In contrast, habitat provision varies from low to high (2–4) in the five segments in the status quo, and

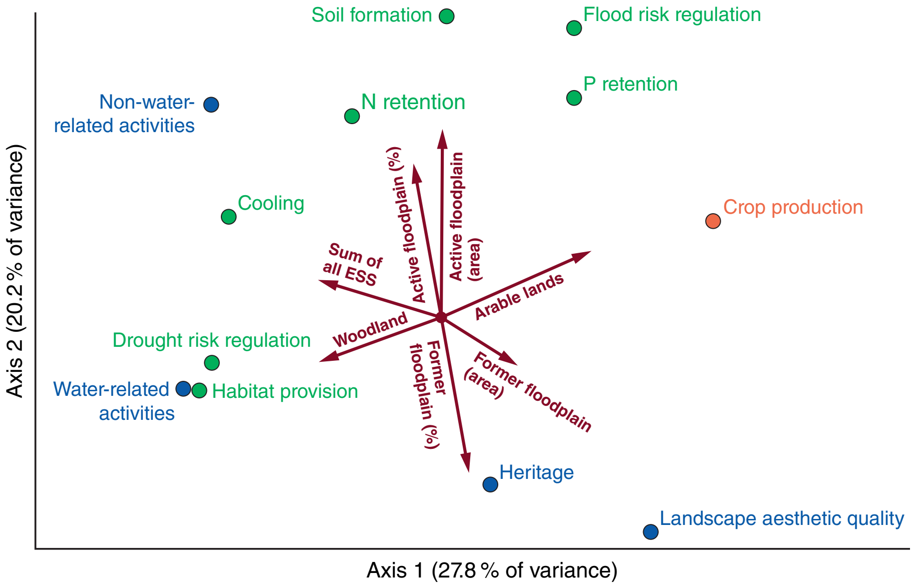


FIGURE 3 Principal component analysis (PCA) of the ES (regulating [green], cultural [blue] and provision [orange]) scores in the 75 1- km segments. Red lines represent correlations with land use data, the connectivity of the floodplain with the river (active or former [diked] floodplain) and with the total sum of all ES scores per segment (only correlations with r^2 > .3 are displayed)

TABLE 2 Spearman rank correlation coefficient (rho) of the ES with spatial land use and floodplain characteristics and with each other

	Crops	N ret	P ret	Flood	Drought	Soil	Cooling	Habitat	LAQ	H	nWA	WA
Land use/floodplain characteristics												
Segment area	**0.47**	0.17	0.27	0.30	−0.17	**0.33**	−0.17	−0.30	0.17	−0.15	**−0.58**	−0.11
Active FP (area)	0.25	0.17	0.26	***0.72***	−0.08	***0.77***	0.19	0.00	−0.20	−0.28	−0.19	−0.18
Active FP (%)	0.08	0.14	0.24	***0.74***	0.00	***0.77***	0.23	0.11	−0.27	−0.23	0.03	−0.16
Former FP (area)	**0.31**	0.03	0.07	−0.30	−0.18	**−0.35**	−0.30	−0.27	**0.36**	0.03	**−0.50**	−0.07
Former FP (%)	−0.06	−0.14	−0.22	***−0.72***	−0.04	***−0.77***	−0.25	−0.12	0.28	0.23	−0.06	0.13
River (area)	−0.23	0.14	0.02	−0.04	***0.63***	0.23	0.12	0.20	0.04	−0.21	0.26	0.24
River (%)	**−0.39**	0.06	−0.11	−0.26	***0.61***	−0.03	0.16	0.24	−0.11	−0.03	**0.49**	**0.32**
Settlements	−0.04	−0.14	−0.17	0.01	0.00	−0.10	**−0.50**	−0.30	0.11	**0.39**	−0.25	0.04
Arable land	***0.70***	0.18	0.30	**0.41**	−0.30	**0.39**	−0.12	**−0.42**	0.06	−0.14	***−0.72***	−0.18
Grassland	−0.03	−0.03	0.03	0.16	−0.01	**0.32**	0.16	0.18	0.08	−0.11	−0.16	−0.04
Woodland	**−0.60**	−0.17	−0.10	−0.28	0.15	−0.29	0.29	**0.37**	−0.03	0.03	***0.81***	0.07
Wetlands	0.13	0.12	0.06	0.00	0.24	0.11	−0.03	−0.08	−0.07	−0.26	−0.18	−0.01
Lakes	0.15	0.14	0.11	−0.01	−0.09	−0.07	−0.09	−0.01	0.17	−0.01	−0.27	−0.11
ES												
Crops		0.28	0.23	0.18	−0.21	0.09	−0.15	**−0.45**	0.01	−0.11	**−0.57**	−0.17
N ret			**0.48**	0.09	**0.36**	**0.33**	0.17	0.05	−0.11	**−0.43**	−0.05	−0.14
P ret				0.30	−0.06	0.22	0.03	−0.05	0.23	−0.24	−0.09	−0.18
Flood					−0.18	***0.76***	−0.03	−0.03	−0.17	−0.08	−0.26	−0.21
Drought						0.11	0.27	0.27	−0.10	−0.24	**0.31**	0.28
Soil							0.21	0.03	**−0.38**	−0.24	−0.15	−0.09
Cooling								**0.36**	**−0.36**	−0.30	**0.50**	0.08
Habitat									0.01	−0.16	**0.58**	0.08
LAQ										0.13	−0.17	−0.06
H											−0.16	0.16
nWA												0.15

Note: Correlation coefficients in bold are considered moderate (rho >0.3), additionally bold-italicized strong (rho >0.6).
Abbreviations: FP, floodplain; H, heritage; LAQ, landscape aesthetic quality; N, nitrogen; ret, retention; (n)WA, (non-)water-related activities; P, phosphorous.

would increase to values between medium and very high (3–5) in Scenario 1, but would decrease to values between very low and medium (1–3) in Scenario 2. N and P retention and soil formation (not shown in Figure 4) would increase the value in two respective three segments in Scenario 1, but would not change in Scenario 2. The sum of ES scores (RESI) would increase in Scenario 1 by 12% and 24 points, respectively, for the five segments, while it would remain more or less the same in Scenario 2, as the increase for flood risk regulation is counterbalanced by the decrease for habitat provision and crops.

5 | DISCUSSION

5.1 | Drivers of ES and bundles of ES along the Upper Danube

Many studies only investigate few ES, whereas more assessments of multiple services and of their interactions are needed (Hanna et al., 2018). We demonstrated that the provision of 13 ES responded differently to land use and floodplain parameters, resulting in a varying sum of the total ES provision along the Danube river section. It is therefore likely that the varying ES will respond to management changes. Similarly, Keele et al. (2019) could not find a clear pattern of the total sum of all ES along their study rivers, whereas Tomscha et al. (2017) could identify fluvial geomorphology as main driver for the provision of ES along the entire river and Large and Gilvear (2015) found increasing ES values in the mid-reaches of rivers and drop off of ES values in the proximity to urban centres. In line with Raudsepp-Hearne et al. (2010), mainly change in land use (arable land vs. woodland) affected the provision of single ES in our study. Additionally, we could support their findings that provisioning ES (crops) show trade-offs with regulating ES as well as with cultural ES. Felipe-Lucia, Comín, and Bennett (2014), in contrast, identified mainly synergies between 12 ES and no trade-offs. The second significant impact on the provision of ES by the percentage of active floodplain in our study indirectly confirms findings of Keele et al. (2019), who demonstrate higher ES provision along rivers with statutory nature conservation designation. According to these highly varying results for different floodplains, each river and stretch must be

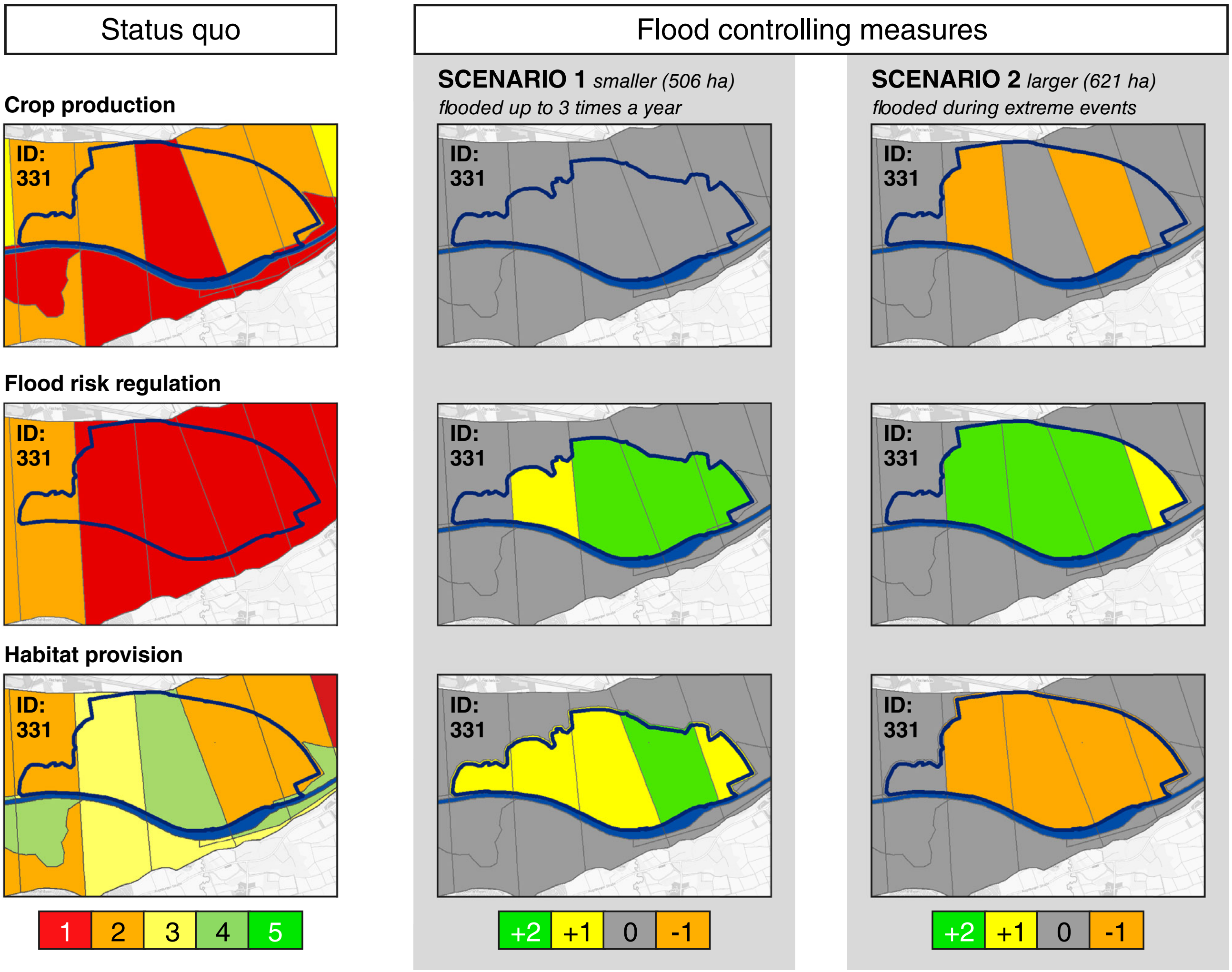


FIGURE 4 Evaluation of three selected ES (crop production, flood risk regulation and habitat provision as indicated) in the segments of the potential polder Leipheim for the status quo (left side), Scenario 1 (middle) and 2 (right side). Values of the colours are explained below the maps. The values represent for the status quo 1 (red)—very low to 5 (dark green)—very high provision of the three selected ES. For the scenarios 0 (grey)—no change, +1 and +2 (yellow and green)—positive and −1 (orange)—negative differences of the three selected ES between Status Quo and Scenario

evaluated on its own relevant set of ES. To get impartial results and for a systematic analysis, a common scale (e.g., 1–5) for all ES, a common methodology of assessment (uniform and comprehensive calculation of ES) and a common assessment area (e.g., 1 km-segments), as shown for the river Nebel by Podschun et al. (2018), should be applied, not only for single floodplains but across different rivers.

Our identification of ES bundles (Figure 3 and Table 2) confirms previous results that ES can be grouped (Felipe-Lucia et al., 2014; Raudsepp-Hearne et al., 2010; Tomscha et al., 2017; Van Looy et al., 2017). The results from the PCA show a clear separation of cultural, provisioning and regulating ES. This underlines the need for comprehensive approaches considering ES of all ES categories as well as the relationships between them when integrative management of river landscape is intended. Similar response of several ES might be estimated based on key ES (in line with Van Looy et al., 2017), however, the large number of proxies and indicators used in our study (land use, hydrological and biological data or soil properties; see Table 1) leads to a great variability of the individual ES and therefore not to a uniform reaction of all ES for instance to land use. Thus, the power of the RESI method (Podschun et al., 2018) to assess and illustrate the diversity of ES provision capacities is clearly demonstrated. A simplified method, for instance using land use data only, may be appropriate for large regions and for historical times for which solely these data are available (Large & Gilvear, 2015; Stammel, Amtmann, Gelhaus, & Cyffka, 2018; Tomscha et al., 2017). Our study shows that in regions with access to more detailed data types, a more precise assessment is feasible which better meets the needs of spatial planning and environmental management.

5.2 | Evaluation of scenarios and further challenges and opportunities for decision-makers

The ES concept is able to support urgently needed integrative floodplain management (Dufour & Piégay, 2009; Hein et al., 2019). Despite some limitations due to time-consuming adaptation of the data for the scenarios for cultural ES which was not conducted here an assessment could help to identify the ES relevant for management decisions or even to estimate reactions when data is missing. Simple maps (Figure 4) or polar charts (Podschun et al., 2018) may illustrate the five-level-scale ES assessments for different scenarios. They can be used in decision-making processes including public participation efforts (Langhans, Jähnig, & Schallenberg, 2019). The joint evaluation scheme of the RESI method makes the results easily comprehensible on a conceptual level. For planning permissions, however, more precise calculations such as detailed spatial modelling of flood risks are necessary. Scenario 1 (ecologically orientated flood control measures) shows various synergies between the ES (N and P retention, soil development, habitat provision, flood risk regulation) and no trade-offs, whereas exclusive flood control measures (Scenario 2) result in significant trade-offs with nature conservation and agriculture. Hence, in case of integrative management, clearly Scenario 1 should be adopted.

Due to our methodological scale, the effects of spatially smaller measures with a width of several meters (e.g., removing embankment, reconnecting floodplain streams) will not show up in the overall evaluation of a 1 km-floodplain segment with a width of several km. Decision-makers thus need to take into account that the here applied RESI method can illustrate only large-scale changes. The approach presented treats all ES equally, to enable an analysis of trade-offs and synergies between the single ES. However, in the planning process stakeholders may prefer weighting of ES regarding their targets or relevance in the region. The RESI approach involves the option to emphasis individual ES in the planning process by applying a weighting rather than a sum. Yet, in order to ensure the integrative management, a comprehensive selection of relevant, but different ES is necessary (Van Looy et al., 2017). At the end, provisioning, regulating, and cultural ES should be balanced (e.g., by normalization of the ES scores and weighting them equally).

6 | CONCLUSIONS

Against the background of the diverse patterns of ES provision along the river course of the Upper Danube in Germany, the need for an integrative river and floodplain management can be confirmed. This study indicates that the ES approach and the RESI methodology are suitable to support stakeholders and decision-makers in this case on the Bavarian Danube. Similar positive effects are to be expected wherever public participation in river management decision-making is mandatory or encouraged. As each river and floodplain is unique, all regionally relevant ES should be evaluated and mapped for the investigated regions. Selecting and weighing the regionally most relevant ES in a well-balanced manner may be useful for decision-making. Management scenarios with minimized trade-offs can be identified as ES respond to management measures in a different way, although bundles of correlating ES exist. Beside a low amount of arable land the size of the active floodplain proves to be particularly important for the provision of many ES including habitat provision for biodiversity. Therefore, revitalizing large parts of historic floodplains should be a priority in environmental policy wherever possible. Our case study shows that the evaluation of a broad range of ES along an extended river section may represent the basis for working across sectoral perspectives and toward a truly integrative river landscape management. Taken all together, we hope that our findings can support water management decision-makers in their efforts to strive for a more integrative planning, policy- and decision-making for more sustainable development of river landscapes for people and nature.

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CONFLICT OF INTEREST

F.F. and A.R. are employed by the company ÖKON Ltd. Association for Landscape Ecology, Limnology, and Environmental Planning. D.M., J.I. and T.H. are employed by the company biota—Institute for Ecological Research and Planning Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

Spatial raw data were provided by various federal and state government agencies and are available upon request. The licenses granted were restricted to the duration of the RESI project. Derived data supporting the findings of this study are available upon request from the corresponding author [BS].

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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